Electric Vehicles as a mobile storage device

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SOMMAIRE

Abstract

Using Electric Vehicles as distributed storage units to obtain some complementary revenues on energy markets could be a way of reducing the Total Cost of Ownership (TCO) of the Electric cars. In order to measure the possible contribution of EV as a mobile storage device, we recall the basic requirements and services needed by Grid Operators to manage the efficient working of an electric power system and of the power system requirements in terms of Frequency, Voltage and Congestion Management. Afterwards, we present the characteristics of economic constraints for storage devices in electricity markets and what could be the potential role of EV fleets in these settings. Finally, we present our simulation about the French case study to show that in 2020, with the new rules provided by ENTSOE, the TCO of EV will be reduced up to a significant proportion according to the user profiles.

1 Introduction to electric power systems

Electricity is a quite recent energy (150 years old) that has developed very much as it allows a flexible use through converters (electrical machines and power electronics). At the beginning, the main use was for lighting and metro. Now, electricity is a major energy for developed countries: 17.7% of the world final energy consumption, and 22 % for the OECD countries(International Energy Agency 2013, figure 1), and an economic growth is always linked to an electric consumption growth. Electricity has improved our daily life: washer, dryer, dishwasher, microwaves, internet, TV, air-conditioning … Humans have become very dependent on electricity consumptions.Nevertheless electricity is a specific product in the sense that it is a non-material energy, and thus it can only be stored through a costly transformation. Electricity can be classified as a tertiary or secondary energy produced from thermal, potential, hydro, wind or solar energy. For a thermal plant, the primary energy (coal, gas, uranium) is converted into mechanical energy (secondary energy) by a turbine and is transmitted to the generator to be converted into electricity (tertiary energy).

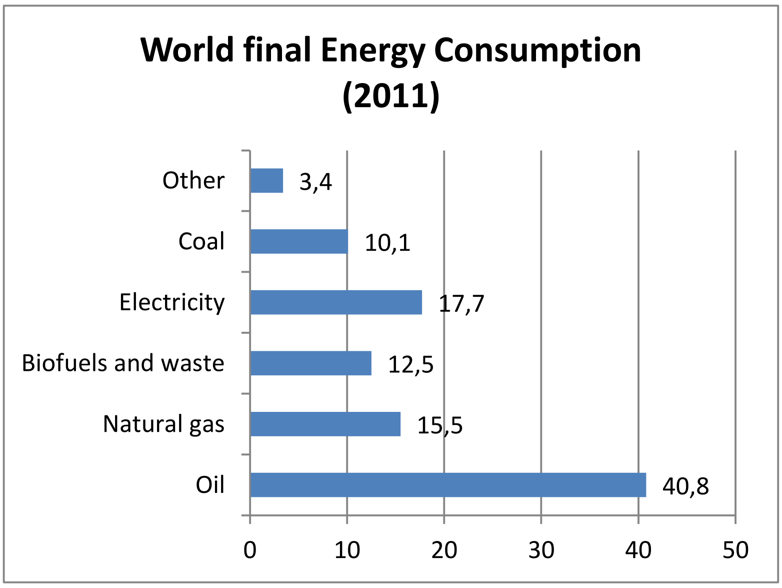

Figure 1: 2011 fuel shares of total final consumption, 8918 Mtoe (IEA report, 2013)

As electricity is difficult to store, it needs an infrastructure to be delivered to consumers: the electrical grid that makes the link between power plants and the consumers through transformers and overhead or cabled lines. At the beginning of the 20th century, all countries made the choice of the alternative current technology as it allowed – thanks to a key device (the transformer) – transmission of high power at high voltages to reduce losses.

In the context of emissions reduction (CO2, NOx…), objectives have been given for cleaner energies and the use of more efficient ones. In Europe there are the "20-20-20" targets: 20% reduction for CO2 emissions, 20% reduction in energy consumption, and 20% increase in efficiency by 2020. To reach these policy goals, electricity is an appropriate vector: it is a flexible energy that can be produced from renewable or CO2 free sources, electrical converters have high efficiency (80-90% for an electric motor) and are bi-directional what makes energy recovery possible for applications such as breaking (trains, vehicles,…). Transportation (cars, autobuses, trucks) is often considered as a major contributor to local pollution. Then constraints for CO2 emissions reduction are more and more severe, especially in Europe. Automakers and their suppliers have optimized their engines with innovations such as start&stop starter/generator, kinetic energy recovery systems, hybrid systems, and full battery electric vehicles and plug-in hybrid vehicles. For the two last cases the energy stored in the batteries will totally or partially come from the electric grid.

2 Main characteristics of electric power systems

The electric power networks are divided into two parts: the transmission grid and the distribution grid. The former links the centralized power plants to the largest consumers and to large substations that feed the distribution grids. The transmission grid has a meshed topology to maintain the continuity of service and to increase the system stability in case of line tripping. In continental Europe, its upper voltage levels are 400 kV and 225 kV, and all national 400 kV grids are interconnected to commercialize electricity and to increase reliability. In each country, the transmission grid is operated by one (France) or several (Germany) operators called transmission system operators (TSO) if the operator owns the grid, or Independent System Operator (ISO) if the operator manages the grids without owning the assets (Rious et al. 2008). The transformers' substations step down the voltage to feed the distribution grid at medium voltage level and then distribution transformers deliver the low voltage to small customers. In that case, the grid has been built with a radial topology to make it easier and cheaper to operate.An important specificity of an electric network is the long lifespan of equipment (several decades) and their sunk costs. Thus any evolutions and investments must be carefully analyzed regarding their impacts on the system security and operation costs.

2.1 Generation mix

A generation mix depends on local available resources and strategic choices. For example, France made the choice for a nuclear generation in the 70's to ensure its energy independence, Norway has a 95% hydro mix due to its resources, and Poland has a 90% coal generation mix. The generation mix is divided into three main categories: base-load plants (nuclear, run-of-river hydro, large coal units), semi-base load plants (coal and gas turbines), and peak load plants (pumped-storage hydroelectricity (PSH), gas or oil combustion turbines). The first oneshave the highest investment costs, but the lowest marginal costs and they are supposed to operate more than 8000 hours per year.Conversely a peak load plant has an equilibrium point at 300 hours of running per year with low investment cost and high marginal costs.

Figure 2 presents the world share of electricity generation. Coal is the main resource (40%) because it is the most abundant onewith an affordable investment cost even if it generates more than one ton of CO_2 per MWh. Nuclear represents only 12% with large disparities between countries because it has the higher investment costs and requires a complex technological knowhow. France has the most important rate of generation from nuclear (~80%) ahead Ukraine (46%). The largest nuclear generation capacity is in the USA (102 GW) ahead France (63 GW) (IEA report, 2013).During the second part of the 20th century generation capacities have been built around large centralized plants connected to high voltage grids (400 kV or more): from 100 MW for a single hydro plant to 1450 MW for some nuclear plants. In an electric power system, the generation capacity must be sized according to the maximum instantaneous demand point, and not regarding the mean value of demand.

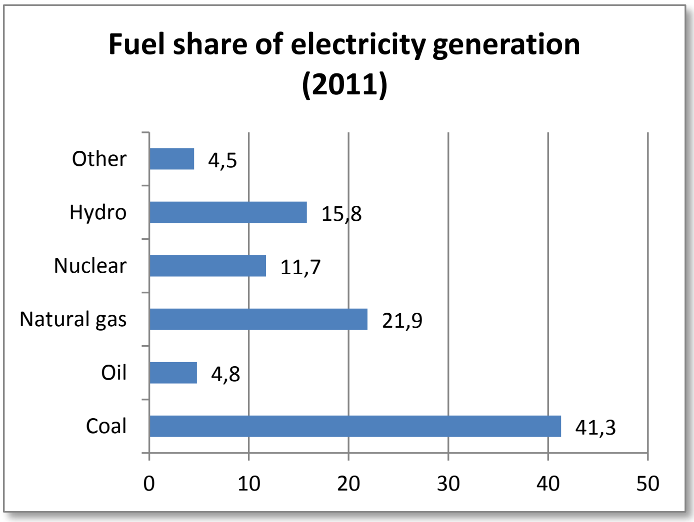

Figure 2 : 2011 Fuel share of electricity generation, 22126 TWh [IEA report, 2013]

Each generation technology has its own dynamic performances that characterize its flexibility, for example: start-up and shut-down durations, ramping limits (MW/s) to increase or decrease the operating point, minimum value of the operating point. The power plant flexibility is critical to safely operate the power system because generation must continuously balance demand to keep the frequency around its rated value (50 Hz in Europe). The optimal generation plan depends on plants marginal costs, plants flexibility, and demand profile. It is the solution of a unit commitment problem (Guan et al., 1992). The figure 3 gives an example of fuel generation sharing for a day in February 2012 (peak-load record in France). The nuclear gives the base-load, then coal and gas. Combustion turbine and hydro plants (flexible) allow fitting the demand. The final difference is completed with importations and distributed generation.

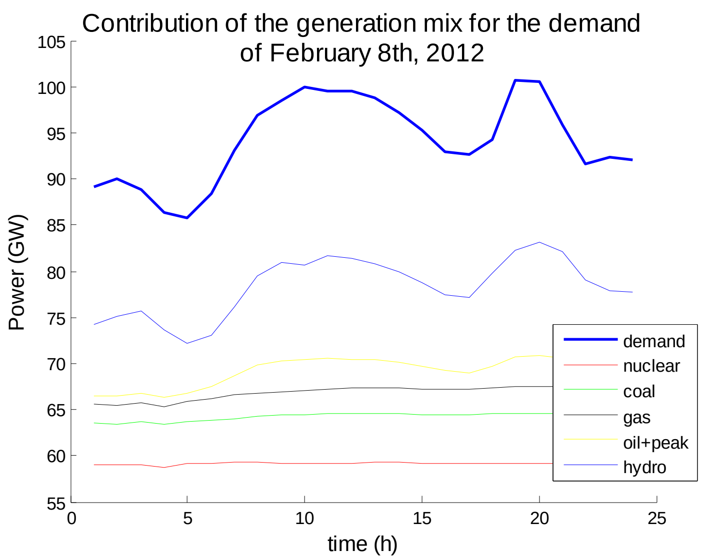

Figure 3: fuel of electricity generation for a single day in winter (France, Feb. 2012)

2.2 Electricity markets

Twenty years ago, the liberalization of the electricity sector has been decided in Europe to improve social welfare. Step by step the incumbent utilities (CEGB in England and Wales, EDF in France, ENEL in Italy, …) have been split into several independent activities: producers, suppliers and grid operators. This evolution has been observed almost all over the world. Electricity markets have been set-up under the supervision of national regulators (Glachant et al. 2013). Presently the interconnected grids are also merging their national electricity markets. The electricity markets have been organized to respect the technical constraints of the electric grids, which main one is: the balancing between generation and demand. Electricity suppliers source with wholesale, day-ahead and intraday markets to minimize their costs while satisfying their customers demand (figure 4). Only predictable generation can be exchanged on wholesale markets. Flexible generators participate to short-term markets (day ahead and intraday), and controllable demand could also participate to these markets.

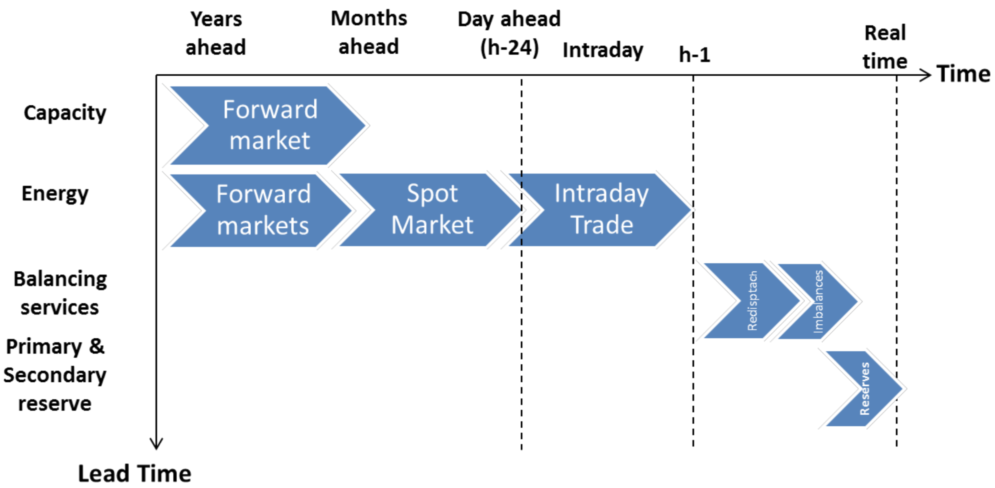

Figure 4: electricity markets organization from long term to real time

2.3 Distributed generation

The emission reduction target is a great opportunity for rolling-out the renewable sources. Hydro plants have been already operated for a long time for flexibility reason. Nevertheless in Europe the hydro potential is almost fully used. Then new sources have been developed: wind, solar or biomass. These sources are often small units that cannot be centralized. Now it is a new paradigm with small distributed generation units (less than 10 MW and down to 3kW for a single unit) connected to the distribution grid. A drawback of these sources is their uncertainties, as wind, sun or wastes are variable (a 1 MW windmill delivers a 0.3 MW mean power) and difficult to forecast precisely. Presently wind forecasts give good results three to six hours ahead. As a consequence, one MW of renewable source cannot strictly replace one MW of thermal power plant.The perfect substitution needs an additional flexible mean that will compensate any generation reduction (hydro or gas turbine, storage).

3 Power system control

The electric power system security is based on the fulfillment at the lowest possible cost of three criteria: frequency control, voltage control and congestionmanagement.

3.1 Frequency control

For an AC system, a single value of the frequency is measured whatever the node inside the grid. This frequency is linked to the generators rotation speed, and its variation is an image of anyimbalance between generation and demand: the rotating parts of the generator behave as a storage system with an increase or decrease of their kinetic energy.Then, to keep the frequency very close to 50 Hz, the mechanical power delivered by the turbines is controlled to follow the demand.As demand always changes, some power plants must be flexible enough to supply a power reserve that must be available at very short time scale (from second to minute). In case of a large amount of variable generation, the grid operator may need more power reserve to ensure the balancing (Ackermann et al. 2007). Finally, controlling the demand may also help the balancing. This is known as demand responseand is a part of the concept of smart grids.

3.2 Voltage control

The second key parameter is the voltage level at each node of the grid. The operators must keep the voltage inside a range to ensure a good power quality to their customers, and to secure the grid stability. In transmission system, the generators mainly control the voltage under the supervision of the TSO-ISO. In radial distribution networks, the load level and line length have a strong impact on the voltage quality. Moreover, the connection of distributed generators (solar, wind…) complicatesand sometime transforms the classical operation of voltage control by the distribution grid operators. In that case a smart demand management can be useful.

3.3 Congestion management

All power equipment (lines, cables, transformers …) are sized for a givenrated current. Any overload will increase losses and then equipment temperature what can reduce their lifespan. Thus network operators take care to prevent any overload by using different technical and economical solutions like redispatching, zonal or nodal market oriented tools (Rious et al. 2008). In a distribution grid, a smart demand management is again a solution to solve this issue.

4 Storage systems: a mean to secure the electric power systems

4.1 General overview

As explained previously, electricity must be generated when it is demanded, but electric energy can only be stored through a physical transformation. The critical balancing between generation and demand can be more flexible if storage systems are available to mitigate the limited flexibility of power plants. Presently the main ones arepumped-storage hydroelectricity (PSH), with a worldwide installed capacity around 127 GW (figure 5). PSH allow both large energy and power, with high flexibility: short response time (couple of minutes), high ramping, and large range between 10% and 100% of the rated power. Such flexibility makes PSH very attractive for the electric power system balancing.

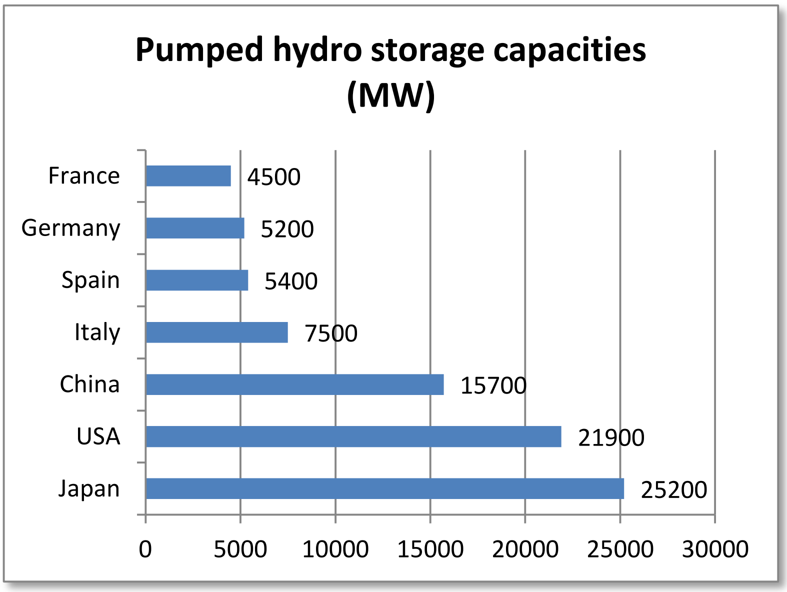

Figure 5: main capacities of installed pumped-storagehydro capacities in the world(Ingram 2009)

High power storage allows flatting the demand curve with an increase demand during off-peak periods and a generation support during peak periods. Depending on energy capacity, the device is used as daily, weekly or seasonal storage.PSH developments depend on natural geographical characteristics that limit their number and size. A recent survey has been published by the JRC, to assess the European potential for PSH(JRC, 2013). Once the PSH potential has been exploited, other solutions must be found out. Any storage device must be assessed along its power and energy potential. Presently centralized storage devices could be Compressed Air Energy Storage (CAES) systems but they require natural cavities, and only few prototypes exist. In the context of distributed energy sources roll-out, small storage systems are also analyzed, with a special focus on battery storage. Experimentations are running in islanding sites with NaS batteries, typical size around 1MW-10MWh (Rious and Perez 2014). The largest system is installed in Rokkasho in Japan (34 MW, 204 MWh).

4.2 Contribution to the system security

In the section 3, three criteria have been described as key elements for the system security. In distribution networks, constraints are mainly the voltage control and the congestion management that are perturbed by the distributed generators (DG).Unfortunately distribution network control and protection schemes have been established under the hypothesis of descending power flows up to the customers. Nevertheless this paradigm is changing, as the connection of a DG to a radial feeder will increase the voltage at the point of coupling. Then to allow the connection of large amount of DG, distributed storage devices could be installed at the critical points of the grid to absorb energy when DG deliver too much power. In a similar way, the storage device can reduce the cables overload to respect their rated current limits.

4.3 Storage economic evaluation is critical

Presently, the economic valuation of storage still remains a critical issue. As highlighted by He and Zachmann (2009), the literature about electricity storage in the power market has mainly focused on the calculation of the arbitrage value of energy bought at a low price and stored and subsequently sold at a higher price. This exercise has been done in several markets (e.g. PJM and New York in the

USA by Sioshansi et al. (2009), Nordpool by Lund et al.(2008)). He and Zachmann (2009) open the research field and determine the return on invested capital of different technologies for different markets, comparing the arbitrage value with the fixed cost of different storage technologies considering their different power ratings. They conclude that for three representative markets in Europe (France, the Netherlands and Scandinavia), no storage facility is profitable despite the benefits they bring to these power systems.

As an example, French spot market prices have been considered for a 1MWh-1MW battery storage system with an efficiency of 90% for a one-way transformation. This battery is charged (1.11 MWh purchased) at the minimum price and discharge at the peak price (0.9 MWh sold). The figure 6 shows that a second cycle per day would not so much increase the benefit.

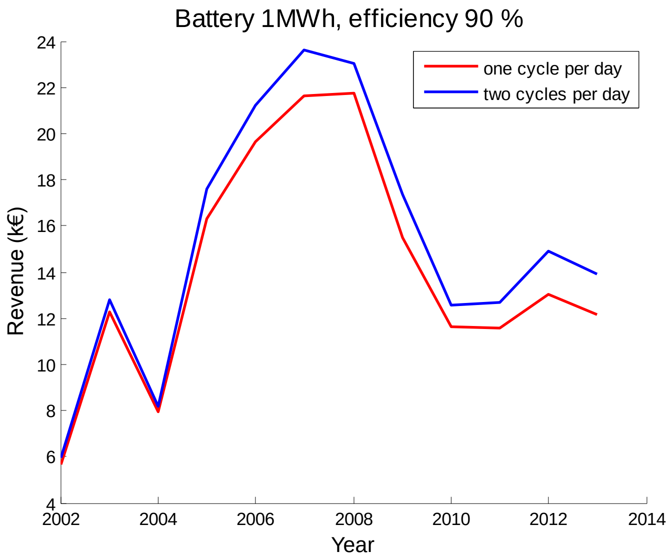

Figure 6: simulation of the revenues when using a 1MW-1MWh battery to capture the difference between peak and base load prices on the French spot market.

5 Plug-in vehicles: opportunities for the electric power systems

5.1 An introduction to Grid Integrated Vehicles

The recent objectives for CO2 emission reduction, as well as those for a decrease in pollution, have revived the interest for electric vehicles (EVs).Indeed, EVs have been provedas being efficient alternatives to conventional vehicles (CVs) in terms of environmental impacts over their entire life cycle (ADEME 2013). As a consequence, most of car manufacturers are launching plug-in hybrid and full electric vehicle models; for the years 2013-2014, 20 different models will be available in the European market.Moreover, authorities implement public policies that aim at promoting EVs: R&D funding, tax reduction, financial incentives for purchasing, and non-financial incentives (e.g. free parking in public places, right to drive on bus lanes…).

However, EV sales are not increasing as expected. For instance, they only accounted for 0.67% of all vehicle sales in 2013 in France, which stands for the first market for EVs in Europe. For the beginning of the year 2014, the market is even down in comparison with the beginning of 2013 (see Figure8). On the global scale, EVs only accounted for 0.02% of the global fleet by the end of 2012 (IEA 2013).

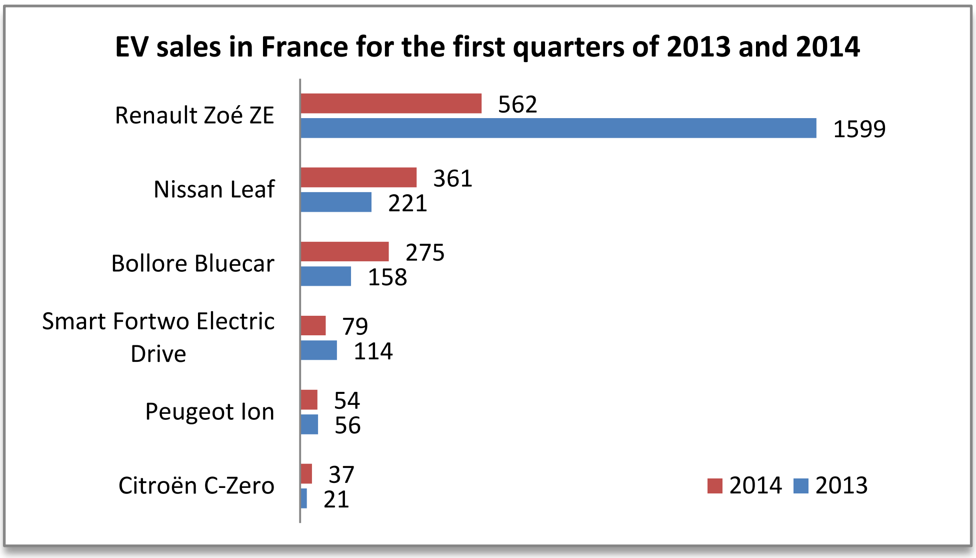

Figure 5:EV sales for each model in France, for the first quarters of 2013 and 2014

The main reason for this is the very high prices of EVs in comparison with their CV counterparts, and this is primarily due to the price of the traction battery (predominantly of Li-Ion technology). Indeed, their cost is around 400€/kWh (IEA, 2013), which leads to approximately 6400€ for a 16kWhbattery.

In order to reduce the Total Cost of Ownership (TCO) of an electric vehicle, one solution could be to use the EV battery as a storage unit for the electric grid when the vehicle is idle.We will call such a vehicle, with additional metering and communication means, a Grid Integrated Vehicle (GIV). The idea is to maximize the use of the battery, either for mobility or for grid services. From a technical point of view, the optimal use must take into account the supplementary aging. The technologies and associated business models for capturing the value and returning part of it to the EV owner, have been developed and demonstrated (Kempton and Letendre 1997; Kempton and Tomić 2005). This solution is possible because EVs have a very good flexibility both in terms of power and availability. For instance, in France, a vehicle is used for transportation averagely 6 hours a week, for a mean daily trip of 21km (Commissariat général au développement durable, 2011). Thus, from the electrical grid perspective, EVs could be available more than 95% of the time. Moreover, considering a rough energy consumption estimation of 0.2kWh/km, EVs would only use 4.2kWh per day, that is, only a quarter of their battery capacity for the smallest batteries. Thus, EVs do not need to charge as soon as they plug-in, what offers a good flexibility for load shifting. Furthermore, not only do EVs have individual flexibility because of their driving patterns, they also have fleet availability because they share the same kind of driving patterns. Some surveys show that more than 80% of a vehicle fleet is always idle at the same time(Pearre et al. 2011).

5.2 Markets available for Grid Integrated Vehicles

Thus, GIVs could operate in electrical markets in order to reduce their TCO. It has been demonstrated that the markets in which GIVs can compete the best are those requiring little amount of energy, but quick responsiveness, and those for which remuneration is based on availability, that is, MW available at each hour (€/MW), and not on utilization(€/MWh)(Kempton and Tomić 2005). This is due to the intrinsic nature of EVs, which are able to modulate their charging rate and switch from charging to discharging mode very rapidly, but which do not benefit from a substantial amount of energy in their battery (although the ratio power/energy is lower than the one of, for instance, flywheels).Table Idisplays several electric markets available, sorted here by characteristic time of solicitation. This table aims at providing insights on the several available markets, not at drawing an exclusive list of them.

Table I: the different electric markets sorted by characteristic time of solicitation

Solicitation characteristic time	Remuneration type	Technological improvements required	Grid services
Second	Availability	Communication means, meters (frequency, power), bidirectionality	- Frequency control(primary and secondary) - Voltage control
Hour or less	Availability and / or utilization	Communication means (possibly)	- Frequency control (tertiary) - Load shifting - Intra-day market - Coupling with renewables - Congestion management - Adjustments - …
Block of several hours	Utilization	Communication means (possibly)	- Load Shifting - Time of Use pricing - Coupling with renewables - Day-ahead market - …

In this table, we make a distinction between the grid services that would induce solicitations on a second, hour or less (say, 30 minutes), or block of several hours basis. The first category requires some hardware and software improvements, but remuneration is based on availability, and these services are highly valuable. The second category is rather broad and includes many different technical solutions. Remuneration can be based either on availability or on utilization, or both at the same time. Eventually, the last category gathers grid services that induce longer solicitations, which are thus less suitable for GIVs. It is noticeable that no specification is made regarding whether these services require unidirectional or bidirectional power flows; indeed, for most these services both cases are possible.The most analyzed technical solutions in the literature are GIV for frequency control, GIV for voltage control, GIV for coupling with renewable and GIV for intra-day market provision.

Frequency control is considered as the most promising grid service for GIVs, as remuneration is based on availability and as it has the highest market clearing prices of all. Thus, many scientific surveys tackle the provision of frequency control reserves by GIVs, such as (Han, Han, and Sezaki 2012) who calculate up to $29400 of revenues during a battery lifetime (say, 10 years) per vehicle. However, some questions are still to be answered, including the battery degradation induced by the participation to this service. The second most discussed issue is the provision of voltage control by EV fleets (Clement-Nyns, Haesen, and Driesen 2011), and it is clear that GIVs could help DSOs to manage the voltage by controllingtheir charging rate. However, very few DSOs value this service presently and a lot of new rules need to be issued in order to allow these services to be provided efficiently by demand response providers. The third service is to ease the integration of intermittent renewableenergy sources.As renewablesenergy sources for electricity are expected to increase significantly thanks to various forms of public support mechanisms, EVs storage provision could help them to be used more efficiently. For instance, Budischak et al. (2013) demonstrate that 99.9% of the demand in the North-East of the US could be met with renewable sources with adapted means of storage, including GIVs.Plug-in vehicles can also be seen as controllable loads that can belong to the portfolio of a curtailment service provider (CSP). At the scale of a building, a mall or a smart/eco-city, this CSP may have optimized direct load control (DLC) actions to deliver a 30 minutes or couple of hours services. Storage capabilities of vehicles could be gathered with HVAC (heating, ventilation, air conditioning) loads. Lastly, EVs could be used to provide intra-day market solutions. This technical solution consists in minimizing the charging costs of a fleet of EVs by taking advantage of the fluctuations of the price of electricity. Usually, this problem is formulated as an optimization problem under constraints (Hoke et al. 2011). The objective function is the total cost of charging for all vehicles, and the constraints stand for battery limits and vehicle needs for transportation. According to the existing surveys conducted on this matter, it seems that this solution is possible with unidirectional power flows, but not profitable with bi-directional power flow (GIVs would charge at low electricity tariff, and sell energy at high prices). This is due to the fact that the difference in electricity prices does not cover the efficiency losses plus the battery degradation costs.

5.3 Scenarios descriptionand Electric Vehicle aggregator definition

Besides these numerous technical solutions described in the previous part, there are several possible configurations for the GIV fleet. In this part, we make a basic distinction between three different scenarios regarding GIV fleetsuses (see Figure). They all differ in terms of EV fleet size, fleet organization (aggregator or not, communications between EVs or not…), EV ownership and grid service provided (as mentioned in 5.2).

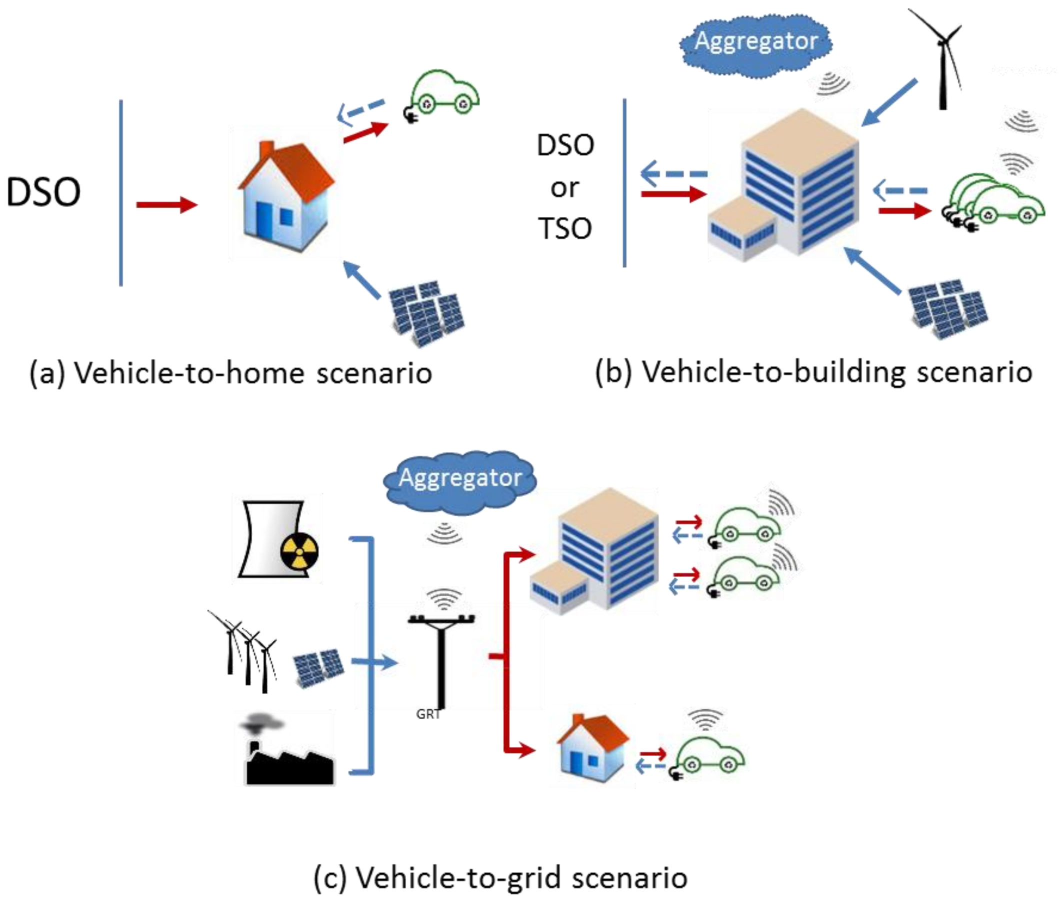

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Figure 8: The different scenarios for GIV fleets

The Vehicle-to-Home scenario deals with a single EV privately owned and plugged-in at home(see figure 8a). In this use case, there is no aggregator and the charging strategy is independent from the other EVs. The services that could be provided are: ensuring home energy security, and some kind of not-dynamic smart charging (e.g. time of use charging triggered each day at the exact same time, no matter the actual situation).

The Vehicle-to-Building scenario deals with EVs are either owned by a company, or belong to a group of people living or working in the same building(see figure 8b). The fleet size is rather small (from a few vehicles in a private parking to a thousand of them in a company fleet). The services provided can be: those already explained in the V2H scenario, some kind of smart charging that requires aggregation and communication, some DSO services (demand-response, voltage control) and, less likely, some TSO services (frequency control). Depending on the service provided, an aggregator may or may not be required.

The Vehicle-to-Grid scenariodeals with thousands up to hundreds of thousands of privately owned EVs controlled by an aggregator (see figure 8c). The services provided could be: TSO services (frequency control), DSO services and some kind of smart charging that requires aggregation and communication. The service provided depends on the fleet size: for instance, it is not possible to provide voltage control with a large fleet spread all over a TSO area, but it is advisable to perform frequency control.In some of these scenarios, the presence of an aggregator is suggested. We need to define more precisely what an aggregator of electric vehicles is.

The notion of aggregator is commonly addressed and employed in market and firm theories. Spulberg (1999) provides a complete review of aggregators and more generally what he calls “market intermediaries". Market Intermediaries benefit from their central rolein the market and they use the good knowledge of the market and economies of scalethey have created to fulfill four main economic roles. First, they ensure “bundling of services” that is packaging various products and services together to facilitate the market functioning and to ensure the satisfaction of market users (producers and consumers). The secondeconomics role of market intermediariesis to manage information to provide the market withproducts, prices and quantities when needed by the market users. Third, market intermediaries play the central role of helping matchingof buyers and sellers in the market. Fourth and last economic role of market intermediariesis to guarantee the liability of all transactions they settled.Because market intermediaries are able to offer these four functions, they can reduce the transaction costs of using the market by providing producers and consumers with the products they need. They prevent market participants from enduring searching and contracting costs, and from getting irrelevant information. Also, they deal with many buyers and suppliers, so they benefit from economies of scale for their own costs. Moreover, as they have a vested interest in having a good reputation, they avert opportunistic behaviors and guarantee that agent’s promises and transfer of property rights will be fulfilled.

The EV aggregator is a specific market intermediary and it is supposed to playa fundamental role in GIV architecture. It is responsible for gathering a fleet of EVs into a single entity. Depending on the grid service provided, aggregators are required for one or more of the following reasons: (a) one single EV cannot provide enough electrical power. Indeed in most of the electricity markets, a minimum size in MW is required to be eligible; (b) TSO do not have the bandwidth for controlling millions of kW size units; they were designed for 100s of multi-MW sized units. Therefore, their data processing capabilities are restricted; (c) TSOs and DSOs expect their resources to be reliable, which is a problem for one EV that gives first priority to transportation, and thus may leave the power system at any moment; and (d) the administrative processes to be eligible and certified for grid services are very complicated and time consuming, thus requiring knowledge and scale effects.

Aggregators can address these issues by controlling large, statistically-reliable fleets. Moreover, they are able to optimize the fleet revenues, by implementing scheduling and dispatching algorithms. They should also be able to deal with a large diversity of degrees of information and degrees of uncertainty induced by many different vehicle types and driver behaviors.

5.4 Grid integrated vehicles and battery degradation

Batteries are the most expensive components of EVs. They account for the substantial difference in price between conventional vehicles and EVs. As a consequence, the profitability of GIVs providing grid services rely on the battery degradation induced by the service provided.Much research has already been conducted to evaluate Li-ion battery wear, sometimes using complex models taking into account the chemical characteristics of the batteries. Battery degradation can be assessed through several aging mechanisms, including internal resistance, internal impedance, static capacity, or stability of the solid electrolyte interface (Broussely et al., 2005).

However, in our case, we will not look into the chemical details, but rather on main macro factors that have an impact on battery degradation. They are described hereafter.

5.4.1 The Depth of Discharge

The variation in state of charge (SOC) performed during each cycle, or depth of discharge (DoD), has a significant impact on battery aging. As shown in(Peterson, Apt, and Whitacre 2010), the higher the DoD of each cycle is, the more important battery wear is. Regarding GIVs, grid services inducing small DoD cycles should be promoted.

5.4.2 The operating State of charge

In addition to the absolute DoD value at which cycles are performed, the SOC range within which these cycles are performed matters. Thus, a 20% DoD cycle does not impact the same battery wear whether it is performed between 40-60% SOC or between 0-20% SOC. Reference (Schmalstieg et al. 2013)provides results regarding this issue, and shows that cycling between 45 and 55% has the smallest effect. On the contrary, cycling at extreme SOC values has a very bad effect on battery lifetime. To conclude, cycles that occur around 50% SOC should be encouraged.

5.4.3 The temperature

Operating at extreme battery temperatures has a negative impact on the battery state-of-health (SOH). The impacts of this factor vary a lot depending on the battery type and are often deduced from laws of physics (such as the Arrhenius law).

5.4.4 The charging rate

Operating at high charging/discharging rate also has a negative impact on the battery SOH. The effects of this factor greatly depend on the EV plug maximum power and on the battery capacity: for instance, if we consider a slow charging station (at home) of 3-5 kW, and a full electric EV battery which capacity is at least 16kWh, the maximum charging rate will be around 0.3C which is pretty low. On the contrary, considering a plug-in hybrid EV battery and a faster charging station (e.g., 7kW) will lead to different results.

5.4.5 Partial conclusion

To sum up, the best services in terms of battery degradation would be those inducing small DoD cycles, performed around 50% SOC, at low rates and ambient temperatures.As a consequence, unidirectional GIVs solutions should not have a negative impact on battery lifetime. On the contrary, the latter could even be increased in the case of GIVs providing services requiring slow charging. Indeed, batteries would be operating less around extreme SOC values, a slow charging rate is beneficial for the battery SOH, and battery temperature would be kept lower than in a fast charge-as-plugged charging application.As for bidirectional GIVs, it depends a lot on the kind of grid service provided and on the control algorithms implemented.

6 Case study: Plug-in vehiclesparticipating to primary frequency control in France

In this part, we present a case study of a fleet of Electric Vehicles participating to primary frequency control in Francein 2020. First, we detail how this control is organized in continental Europe (ENTSOe area where ENTSOe is the association for TSOs in Europe), and the assumptions we make towards the evolutions of the rules in 2020. Then, we model the behavior of the EV fleet. Afterwards, the algorithms and simulation parameters are presented. At last, we display and discuss the results.

6.1 Primary frequency control in France

The primary frequency control is organized at the ENTSOe level to ensure a 3000 W reserve. In France, the primary reserve contribution is around 700MW. For any frequency deviation in -200mHz and +200mHz, units that are part of this reserve have to respond according to equation (1):

$$P_i - P_{i_0} = \min(P_{primary\ \ reserve}\ ; K_i * (f - f_0)) \qquad (1)$$

with P_i, P_{i0} and $P_{primary\ reserve}$ respectively the power for regulation, the operational point and the power reserve of the i^{th} unit dedicated to the primary frequency control, f the current frequency, f_0 the nominal frequency and K_i the frequency droop of the unit. The value of the frequency droop is decided by a common agreement between the unit in question and the French TSO (RTE). Figure 9 presents the traditional power-frequency curve of a resource.

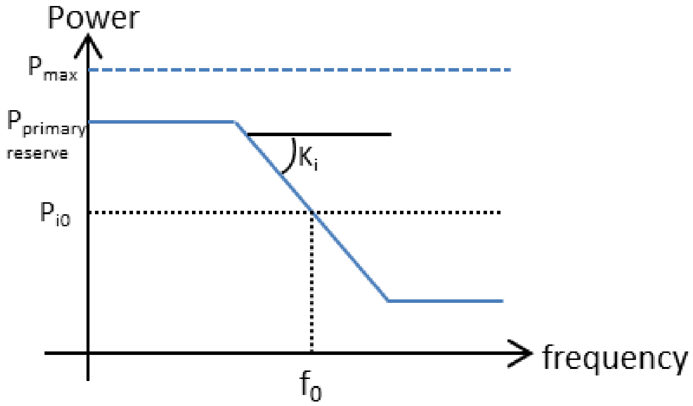

Figure 6 : Primary frequency response for a traditional unit

Moreover, unit responses have to comply with the following requirements(UCTE, 2004):

- Half of the power available for regulation should be delivered in 15 seconds, and all of it in 30 seconds
- Frequency measurements must have an accuracy better or equal to 10mHz
- A frequency dead-band of 20mHz is allowed
- Frequency measurement period must be between 0.1 and 1 second

From an economic perspective, the primary reserve is dispatched among the different units willing to participate by the TSO, based on their expected ability to provide power for regulation. Thus, for each 30-minute period, RTE allocates a given power to each unit, which are then remunerated based on the fixed tariff of 8.48€/MW per 30 minutes.

The aforementioned technical rules are not likely to change in a close future, because they are bound by safety reasons. On the contrary, the way RTE allocates the primary reserve and remunerates the units may change substantially in the coming years. Indeed, the new network codes of ENTSOE should come into force within the next three years, and should induce important changes for RTE rules.

First, the primary control will have to be organized via an auction market, and avoid barrier for new entrants (ENTSOE, 2013). A framework particularly adapted for storage units and controllable loads is mentioned in (ENTSOE, 2012): Demand Side Response Very Fast Active Power Control (DSR VFAPC). As a consequence, and considering that we target 2020 and based on other TSO surveys (Codani, Perez, and Petit 2014), we assume that the primary control is organized via an hourly auction market (as it is in Denmark or in some regions in the USA for example). The EV aggregator makes an offer (composed of a capacity and a price) for every hour, which is then either accepted or rejected by the TSO. Obviously, we assume that EV aggregation is allowed, as suggested in (ENTSOE, 2013b). At last, we keep a symmetrical market, that is, the amount available for regulation UP and the one for regulation DOWN should be the same for each tender. In absence of a public database on frequency measurement in Europe, we build our own limited dataset. In order to do so, we used a five working day recordings frequency data set, from March 28th to April 1st 2014 in Supélec Paris. These measures were performed with a frequency measurement device, with a 1 second period and an accuracy of 1mHz, thus abiding by ENTSOE requirements.

6.2 Electric Vehicle fleet modeling

6.2.1 Electric Vehicles' characteristics

According to the IEA (IEA 2013), there should be 2million EVs on the roads in France by 2020. However, considering the EV sales of 2013, this target seems too optimistic. Furthermore, it is obvious that not all of EVs will join a frequency control program. As a consequence, we decide to model a fleet of only N_{VE} = 200,000 EVs.

The battery size bears little importance on the results because primary control induces mainly power solicitations (in contrast with energy solicitations). Moreover, 64% of French EVs in 2013 had a battery size of 22kWh. As a consequence, we will consider that all our EVs have a 22kWh battery, and we introduce the constraint $0.2 < SOC/SOC_{max} < 0.9$ in order to prevent the batteries from reaching too extreme state-of-charge (SOC) values.

6.2.2 Electric Vehicle Supply Equipments'characteristics

The characterization of the Electric Vehicle Supply Equipments (EVSEs), or charging stations, is important because the latters will set power exchange levels between the grid and the vehicles. As explained in **Erreur ! Source du renvoi introuvable.**, we narrow the fleet trips to the sole commuting trips. Then, there are two charging possibilities for EVs: at home on the *primary EVSE* and at work on the *secondary EVSE*. We consider "one EV, one EVSE" for the *primary EVSEs*, that is, all EVs have an EVSE at home. Regarding the number of *secondary EVSEs*, as we do not know precisely yet how many EVSEs will be installed at working places in France by 2020, we model four different scenarios presented in Table II.

Table II: The four scenarios for secondary EVSEs penetration levels

Scenarios	Ratio of Electric Vehicles having an EVSE at work
Scenario 1	0%
Scenario 2	25%
Scenario 3	50%
Scenario 4	75%

There are four different maximum charging rates, which correspond to French current and voltage standards: the so-called *slow charging* at 3kW (230 V,1-phase, I=16A) or at 7kW (230 V, 1-phase, I=32A), *intermediate charging* at 22kW (400 V, 3-phases, I=32A) and *fast charging* (400 V, 3-phases, I=64A or DC charging). Depending on the charging location, we consider that EVSEs are distributed according toTable III.

Table III: the different electric markets sorted by characteristic time of solicitation

EVSE charging level	Primary EVSES	Secondary EVSEs
Slow charging – 3kW	95%	35%
Slow charging – 7kW	5%	34%
Intermediate charging – 22kW	0%	29%
Fast charging – 43kW	0%	2%

6.2.3 Electric vehicle use for transportation

EVs are first used for transportation, so we need to model the primary use of EVs. Then the four data we need are: (a) the number of trips per day for each vehicle; (b) the duration of each trip; (c) the departure times; and (d) the energy consumption.We assume that the EVs are used only for commuting. We are then able to run simulations for 5 working days with our frequency data set. The average daily driven distance d is taken from intern surveys conducted by PSA Peugeot Citroën, to which we add a Gaussian uncertainty:

$$d \sim N(d_{PSA}; \sigma)$$

with σ = 5km. From this distance, we deduce the trip duration by means of an average speed v_{avg}, itself also taken from intern PSA Peugeot Citroën surveys.

Departure times are also distributed according to Gaussian laws, for which we choose means and standard-deviations corresponding to usual commuting departure times. At last, the energy consumption is taken from data coming from the Cross-border mobility for EVs (CROME) project, which made some of its data publicly available. We come up with a distinction between summer and winter consumptions: c_{summer} = *129Wh/km* and c_{winter} = *184Wh/km*.

6.3 Algorithms & parameters

6.3.1 Dispatch algorithm

We assume that the scheduling algorithm is fully efficient, and we do not simulate it. In other words, the aggregator tenders are always accurate regarding the actual available power for regulation, and the offered price is always accepted by the TSO.The dispatch algorithm, which aims at dispatching power flows among the several EVs, is closely related from the one implemented at the University of Delaware demonstration project. In this project, fifteen electric vehicles are gathered in a coalition, which is registered as a resource and fully compliant with PJM (the regional system operator) rules. These EVs take part into the secondary (also called regulation) market. More details on this project and the algorithm are provided in (Kamboj, Kempton, and Decker 2011).

Our algorithm is based on the following steps:

1) Let t be the current time (in seconds), *POP* the *preferred operating point* and δt the POP update period, which we set to 1 hour. The *POP*corresponds to theamount of production or consumption of a vehicle withouttaking into account the participations to frequency control. For instance, a unit with a*POP* equal to P_0required to provide p_1 for frequency control will change its consumption point to $P_0 \pm p_1$ depending onthe request sign. If $t \equiv 0[\delta t]$, the POP and the available power for regulation P_{reg} are computed by each vehicle according to equation 2(Kamboj, Kempton, and Decker 2011), and then communicated to the aggregator:

$$\begin{cases} POP(t) = \frac{1}{2}(P_h + P_b) \\ P_b = min\left(P_{max}, \frac{SOC - E_{min}(t + \delta t)}{\delta t}\right) \\ P_h = -min\left(P_{max}, \frac{SOC_{max} - SOC}{\delta t}\right) \\ P_{reg}(t) = P_{max} - |POP(t)| \end{cases} \quad (2)$$

with *SOC* the state of charge of the battery, $E_{min}(t)$ the minimum SOC required at time t to ensure next trip, SOC_{max} the maximum SOC et P_{max} the maximum power limited by the facilities. We assume that the drivers provide the aggregator with information regarding their next trip: energy required, and departure times.

2) The aggregator measures the frequency, and depending on the current power that was bid in the market P_b, deduces the power P_r to be dispatched among the vehicles:

$$P_r = \begin{cases} \frac{f - f_0}{f_{max} - f_0} P_b, & |f - f_0| < 0.2\ Hz \\ P_b, & |f - f_0| \geq 0.2\ Hz \end{cases} \quad (3)$$

with $f_0 = 50Hz$ and $f_{max} = 50.2Hz$.

3) Then the aggregator computes a correction factor µ, in order to match the available power from the vehicles and the power to be provided to the grid

$$\mu = \frac{P_r}{\sum_{i=1}^{N_{VE}} P_{reg_i}} \quad (4)$$

4) Finally, the aggregator informs EVs with the power they have to actually provide, equal to $\mu * P_{reg_i}$
5) Repeat from step 1) if $t \equiv 0[\delta t]$, step 2 otherwise.

Figure 107sums up the algorithm operating principle.This scheme is repeated for every new frequency measure, i.e. every second.

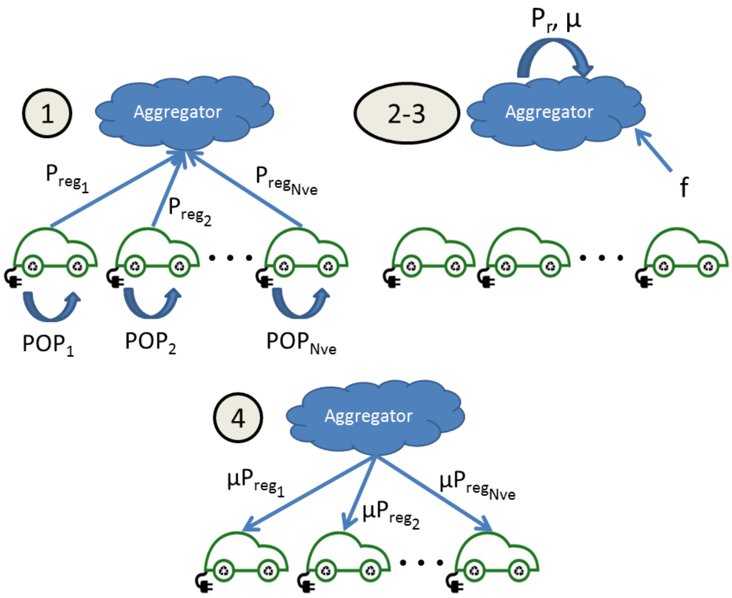

Figure 107: Dispatch algorithm scheme

It is noticeable that the algorithm implemented is a decentralized solution (see hces034). We decided to use such an algorithm because centralized algorithms do not give much better results (Vandael et al. 2013), but they require much more computation time, and the used algorithm has been proved efficient in a real demonstration project. shows the simulation results for a single EV over 5 working days.In this figure, the EV understudy is not able to charge at work, that is why the SOC is steady for some long periods (e.g. from 35h to 40h). At home, the EV participates to frequency control (e.g. from 65h to 80h). When the next trip is in a long time, the POP is null, and the power available for regulation is maximum. As the next trip is getting sooner and sooner, the minimum SOC required E_{min} increases, and consequently the POP decreases (negative values stand for charging) and the power available for regulation decreases.

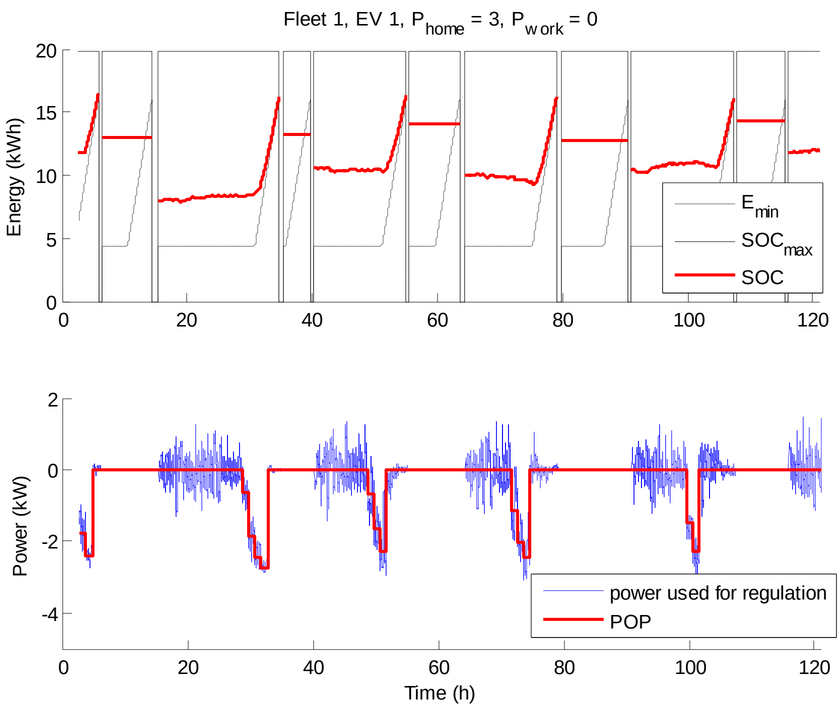

Figure 118: Results of a simulation for a single EV over 5 working days

6.3.2 Other simulation parameters and results

In order to perform an economic evaluation, we need to use auction remuneration prices to deduce EV earnings from their power available for regulation. As explained in **Erreur ! Source du renvoi introuvable.**, we assume that primary control is organized via an auction market, and thus it would not be relevant to use the stated administered tariff of RTE. As a consequence, we will use market-clearing prices from Energinet.dk primary control market. Energinet.dk is a Danish TSO, whose clearing prices are available on the internet (Energinet.dk 2013). As for the energy consumed during the trips, we make a distinction between two seasons for the prices: a "summer" season, for which we use prices from quarters 2 and 3 of 2013, and a "winter season for which we use prices from the last quarter of 2012 and the first one of 2013. For each 5 working dayssimulation, we randomly select 5 continuous days of hourly clearing prices.

For each scenario, we made ten simulations for a hundred vehicles with the parameters "summer" and ten other simulations with the parameters "winter". The results are presented in the following section, either per vehicles or scaled to match a fleet of 200.000 vehicles.The simulation results are presented in Table IV.

Table IV: Results: hourly minimum and average power delivered by the whole fleet, and average remuneration per vehicle, for 5 day simulations

Scenarios	Hourly Minimum Power (MW)	Hourly Average Power (MW)	Average earnings per vehicle (€)
Scenario 1	1.6	311	2.97
Scenario 2	6.5	501	5.00
Scenario 3	11.4	692	7.04

Scenario 4	16.2	882	9.08

We can see that the penetration of EVSEs at working places has a significant impact on the expected fleet remuneration. We find a factor of three betweenscenarios 1 and 4. Although earnings are lower for scenario 1, they are not negligible: even without taking into account the week-ends, because EV uses are much more erratic, we reach 150€ per vehicle and per year considering 251 working days in a year. For scenario 4, these earnings reach more than 450€per year and per vehicle.

7 Conclusion

Grid Integrated Vehicles are plug-in vehicles that are used as distributed storage. They can support the grid by providing various ancillary services. The most promising ones are voltage control, congestion management, intra-day markets and, above all, frequency control. Based on our calculations, it seems that in 2020, GIVs will be capable of reducing the Total Cost of Ownership (TCO) of an electric vehicle by maximizing the use of the battery, either for mobility or for grid services of a significant volume in the French case. Of course a lot of points could be improved or challenged in our approach to estimate the GIV contribution to the reduction of electric car TCO. For instance in the French case, we need to get more frequency data over the year to account for seasonal effects, we also would like to take into account different kinds of EV fleets (professional uses for taxis or postal services…). We also need to better understand the impact of GIV on the lifespan of the battery wear.However, our simulations can pave the way to similar works with the existing different market designs across the countries.

8 References

ADEME. 2013. “Elaboration Selon Les Principes Des ACV Des Bilans Energetiques, Des Emissions de Gaz À Effets de Serre et Des Autres Impacts Environnementaux Induits Par l’Ensemble Des Filieres de Vehicules Electriques et de Vehicules Thermiques, VP de Segment B et VUL.”

Broussely, M., Ph. Biensan, F. Bonhomme, Ph. Blanchard, S. Herreyre, K. Nechev, and R.J. Staniewicz. 2005. “Main Aging Mechanisms in Li Ion Batteries.” *Journal of Power Sources* 146 (1-2) (August): 90–96. doi:10.1016/j.jpowsour.2005.03.172. http://linkinghub.elsevier.com/retrieve/pii/S0378775305005082.

Budischak, Cory, Deanna Sewell, Heather Thomson, Leon Mach, Dana E Veron, and Willett Kempton. 2013. “Cost-Minimized Combinations of Wind Power , Solar Power and Electrochemical Storage , Powering the Grid up to 99 . 9 % of the Time.” *Journal of Power Sources* 225: 60–74.

Clement-Nyns, Kristien, Edwin Haesen, and Johan Driesen. 2011. “The Impact of Vehicle-to-Grid on the Distribution Grid.” *Electric Power Systems Research* 81 (1) (January): 185–192. doi:10.1016/j.epsr.2010.08.007.

Codani, Paul, Yannick Perez, and Marc Petit. 2014. “Diversity of Transmission System Operators for Grid Integrated Vehicles.” In *11th International Conference on European Energy Markets*.

Commissariat général au développement durable. 2011. “Les Véhicules Électriques En Perspectives.”

Energinet.dk. 2013. “Energinet.dk Market Clearing Prices.” http://energinet.dk/EN/El/Engrosmarked/Udtraek-af-markedsdata/Sider/default.aspx.

European Network of Transmission System Operators for Electricity. 2012. “Network Code on Demand Connection.” https://www.entsoe.eu/major-projects/.

———. 2013a. “Network Code on Electricity Balancing.” https://www.entsoe.eu/major-projects/.

———. 2013b. “Network Code on Load-Frequency Control and Reserves.” https://www.entsoe.eu/major-projects/.
Han, Sekyung, Soohee Han, and Kaoru Sezaki. 2012. “Economic Assessment on V2G Frequency Regulation Regarding the Battery Degradation.” *Innovative Smart Grids Technologies (ISGT), 2012 IEEE PES*.
Hoke, Anderson, Alexander Brissette, Dragan Maksimovic, Annabelle Pratt, and Kandler Smith. 2011. “Electric Vehicle Charge Optimization Including Effects of Lithium-Ion Battery Degradation.” *2011 IEEE Vehicle Power and Propulsion Conference* (September): 1–8. doi:10.1109/VPPC.2011.6043046. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6043046.
Ingram, Elizabeth. 2009. “Pumped Storage Development Activity Snapshots.” *Hydro Review* 17 (6): 12–25.
Internation Energy Agency. 2013. “Global EV Outlook.”
JRC Scientific and Policy Reports. 2013. “Assessment of the European Potential for Pumped Hydropower Energy Storage.”
Kamboj, Sachin, Willett Kempton, and Keith S Decker. 2011. “Deploying Power Grid-Integrated Electric Vehicles as a Multi-Agent System.” *10th Int. Conf. on Autonomous Agents and Multiagent Systems - Innovative Applications Track (AAMAS)* 1 (Aamas): 2–6.
Kempton, Willett, and Steven Letendre. 1997. “Electric Vehilces as a New Power Electric Utilities Source for Electric Utilities.” *Transportation Research Part D: Transport and Environment* 2 (3): 157–175.
Kempton, Willett, and Jasna Tomić. 2005. “Vehicle-to-Grid Power Fundamentals: Calculating Capacity and Net Revenue.” *Journal of Power Sources* 144 (1) (June): 268–279. doi:10.1016/j.jpowsour.2004.12.025. http://linkinghub.elsevier.com/retrieve/pii/S0378775305000352.
Pearre, Nathaniel S., Willett Kempton, Randall L. Guensler, and Vetri V. Elango. 2011. “Electric Vehicles: How Much Range Is Required for a Day’s Driving?” *Transportation Research Part C: Emerging Technologies* 19 (6) (December): 1171–1184. doi:10.1016/j.trc.2010.12.010. http://linkinghub.elsevier.com/retrieve/pii/S0968090X1100012X.
Peterson, Scott B., Jay Apt, and J.F. Whitacre. 2010. “Lithium-Ion Battery Cell Degradation Resulting from Realistic Vehicle and Vehicle-to-Grid Utilization.” *Journal of Power Sources* 195 (8) (April): 2385–2392. doi:10.1016/j.jpowsour.2009.10.010. http://linkinghub.elsevier.com/retrieve/pii/S0378775309017443.
Schmalstieg, Johannes, K Stefan, Madeleine Ecker, and Dirk Uwe Sauer. 2013. “From Accelerated Aging Tests to a Lifetime Prediction Model : Analyzing Lithium-Ion Batteries.” In *Electric Vehicle Symposium 27*.
Spulberg, Daniel F. 1999. *Market Microstructure: Intermediaries and the Theory of the Firm*. Edited by Cambridge University Press. Press Syndicate of the University of Cambridge.
Union for the Co-ordination of Transmission of Electricity. 2004. “Operation Handbook.”
Vandael, Stijn, Tom Holvoet, Geert Deconinck, Sachin Kamboj, and Kempton Willett. 2013. “A Comparison of Two V2G Mechanisms for Providing Ancillary Services at the University of Delaware.” *IEEE International Conference On Smart Grid Communications*.